NOAA's Ocean Observing Programs

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Abstract

The National Oceanic and Atmospheric Administration (NOAA) has the broadest and most complex ocean mandate of any Federal agency, and an array of observation programs to match. While those observing programs were developed to serve that diverse set of mission needs, NOAA recognizes the benefits of moving toward more integrated approaches. We describe the current suite of NOAA's observing programs from the perspective of its mission, goals, and strategies, with a particular emphasis on meeting internal and external user needs. In addition to outlining NOAA's potential contributions to the emerging interagency and international network of ocean observing systems, we offer some perspectives on the characteristics of such a system from the perspective of an organization that would both feed it and use it.

NOAA's Mission, Goal and Strategies

NOAA's mission—"to understand and predict changes in the Earth's environment and to conserve and manage coastal and marine resources"—is the broadest ocean mandate of any Federal agency. As such, it has virtually sole responsibility for some of the six goals of the original Global Ocean Observing System (GOOS) defined by the Intergovernmental Oceanographic Commission (e.g., sustain living marine resources), lead responsibility for other goals (e.g., improve climate predictions), and important responsibilities for all of the other goals (improve marine operations, mitigate natural hazards, minimize public health risks, protect/restore healthy coastal marine ecosystems). As a primarily operational agency, with long and numerous international tentacles, NOAA can help provide the leadership needed to make integrated global ocean observing a reality.

NOAA's strategic goals to: 1) protect, restore, and manage the use of coastal and ocean resources; 2) understand climate variability and change; 3) serve society's needs for weather and water information; and 4) support the Nation's commerce with information for safe, efficient, and environmentally sound transportation also align with the original GOOS plan. Attempting to reach these goals without routine, reliable, sustained, and credible observations would be like playing pinball blindfolded. While Tommy from The Who's rock opera might have been able to do that, NOAA employs no pinball wizards. Therefore, over time it has created an array of observing programs that respond to those diverse goals and challenging missions. New technologies and new strategies now offer, for the first time, the potential for integrating and obtaining more value from these efforts both to support its missions and to contribute to the emerging government-wide and international Earth observing system.

While this broad set of missions requires observing programs that extend from the bottom of the ocean to the surface of the sun, we focus in this paper on its ocean observing. For the purposes of this paper, we define "ocean" to include the physical, chemical, and biological constituents, and the bottom substrates and shorelines, of the waters in global ocean basins and U.S. coastal regions (i.e. bays, estuaries, ports, harbors, and the continental shelf), as well as properties of adjacent U.S. lands and watersheds. While one might not normally consider land and watersheds as components of an ocean observing system, NOAA's strategies to understand, assess, and predict change in the coastal ocean require understanding and observing change in the lands adjacent to it. We include sustained observing efforts from our operational programs and from research efforts with life-cycles greater than 10 years because many components of our observing systems derive from those national and international research programs. For example, the El Niño/Southern Oscillation (ENSO) Observing System, which incorporates a variety of sustained measurement programs in the tropical Pacific, grew from 1985-1994 Tropical Ocean-Global Atmosphere (TOGA) research program. Global extensions of the surface drifter, Argo float, voluntary observing ships, ocean reference station, and tide gauge networks were developed in the 1990-2002 World Ocean Circulation Experiment (WOCE). We anticipate new biological and chemical observing systems to emerge from the current suite of long-range research programs, such as the Global Ocean Ecosystem Dynamics (GLOBEC) and Ecology and Oceanography of Harmful Algal Bloom (ECOHAB) programs.

While we do not include them in this survey of ocean observing programs, NOAA also collects a wide array of data on fisheries and other social and economic activity in coastal areas, including multimillion dollar recreational fisheries surveys, commercial fisheries yield, economic and participation data, and community profiling. These data are as important as those from the natural environment for our resource management missions.

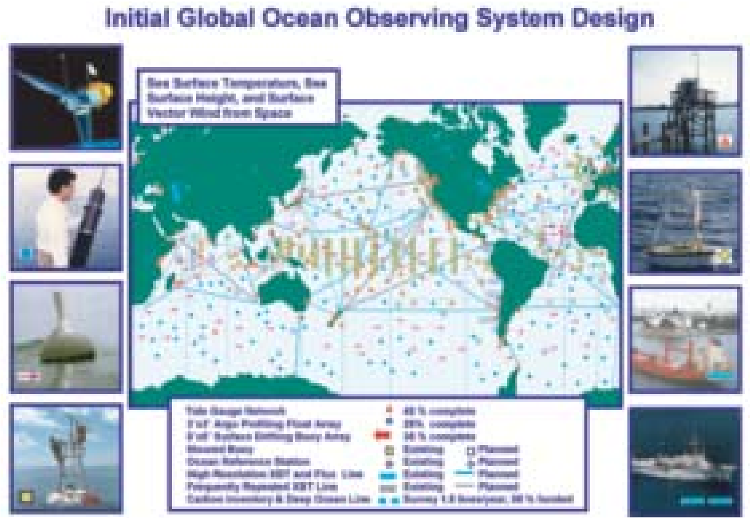

Figure 1. *Illustration of the planned Global Ocean Observing System with an emphasis on the Climate Module. (Photo courtesy Mike Johnson, NOAA/Office of Global Change.)*

Users of NOAA Data and Information

The primary drivers for NOAA's ocean observing programs are the requirements for meeting our operational missions of fisheries, protected species, habitat, sanctuary, and estuarine reserve management; operational support for marine transportation; and weather and climate forecasting. However, we also serve the needs of the broader community. For example, of the 59 coastal and ocean observational parameters prioritized by users ranging from research and operational oceanographic and fisheries communities, to commercial, non governmental organizations, public health, and private constituencies at the Ocean.US workshop in March 2002 (Ocean.US 2002), NOAA collects data, albeit with widely varying and often under sampled spatial and temporal sampling schema, for each of the top 50% priority parameters.

NOAA's observing systems, described in the next section, have been shaped by its heritage. When NOAA was established in 1970, it became home for weather, ocean, and coastal activities from an array of bureaus and agencies from across government. Each brought to the then new organization key observing efforts that have, more or less, survived to this day. Emerging from that history, the clear imperative for improved weather forecasting forced integration of major observing and communications systems in response to an expanding and increasingly well-defined user base. In a similar way, although more recent, the clear imperative to improve climate forecasts has helped coalesce that community around climate observing systems that include ocean observing. Although incomplete, many of the weather and climate observing tools are in place to serve those communities.

In contrast, coastal and ocean user communities are far more diverse and less well organized, and observing efforts have been tailored to meet more specific needs. For example: water levels, tides, currents, nautical charting, and shoreline mapping support marine transportation; surveys of living marine resources support fisheries management; weather and currents support offshore energy production management; and habitat and water quality support estuarine and marine protected areas management. And we now know that the ocean and atmosphere are not only linked and collectively influence weather and climate, but that fisheries, transportation planning, coastal management and protection, and energy forecasts all benefit from improved ocean-atmosphere predictability (Flemming, 2001). We also know that modern capabilities of high-resolution bathymetric and shoreline mapping, integrated with geodetic and water level reference datums, can provide baseline maps required for a wide variety of non-navigation applications such as coastal inundation and benthic habitat maps. The challenge is finding ways to share these individual data streams in ways that meet the larger challenge and serve this economically important, but more diverse, community of users.

Travel and tourism to the nation's coasts, whose long-term viability depends on water quality and coastal planning, is a multi-billion annual business yet the footprint of this business and associated user groups is fragmented across numerous towns, counties, and states. Recreational and commercial fisheries, and other living marine resource based industries, such as whale watching, contribute tens of billions to the national economy, and they are key contributors to travel and tourism, as well has providing high quality protein, and supporting domestic and international trade. Yet despite the enormous economic value from these industries, many of the observations taken to support them, particularly non-physical properties, have not historically been considered part of operational observing per se; although such observations

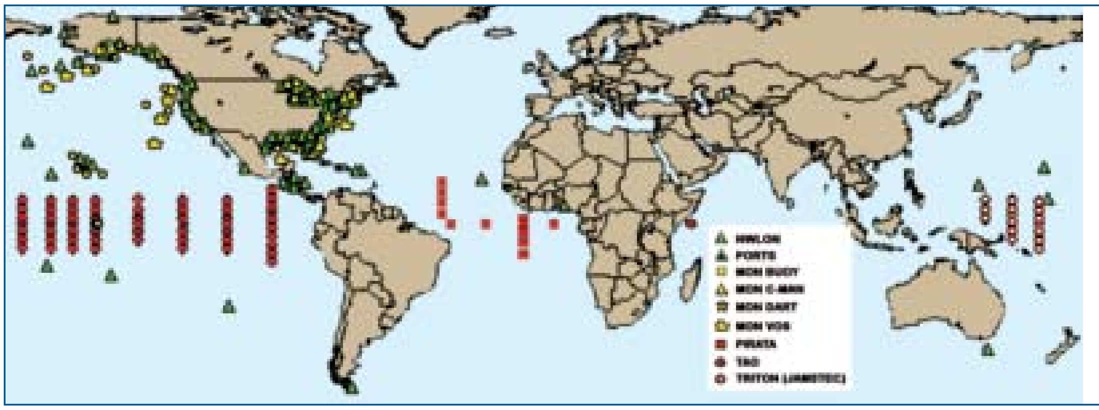

Figure 2. *Location of NOAA supported moorings and arrays including both Climate and Coastal Modules*

have a longer history (some over 50 years), cover more territory (over a million square miles of the U.S. EEZ), and cost more (hundreds of millions of dollars) than most other observing programs.

While the challenges are significant, advances in data management and sharing protocols, improvements in observation technology, and the recognition of the needs of this broader community within the Integrated Ocean Observation System (IOOS) planning framework provide new contexts for contributions from NOAA's long-standing and emerging observing programs.

NOAA's Ocean Observing Programs

NOAA's ocean observing platforms range from global and coastal tide stations networks, coastal and tropical moorings, and arrays of surface and profiling drifting buoys to a dedicated fleet of small and large vessels, ships of opportunity, aircraft, and satellites. While most observing efforts were developed originally to support the long-standing missions of weather prediction, marine transportation, and fisheries and coastal management, many have been extended to new missions, most notably climate. For example, NOAA is participating in an international effort to fully implement an ocean observing system for climate by 2010. The system will serve not only our climate missions, but also to support some of our marine and coastal forecasting mandates (Figure 1).

We describe NOAA's ocean observing efforts in the following platform categories: 1) autonomous fixed platforms, 2) tide station networks, 3) oceanographic vessels, 4) drifting and profiling buoy networks, and 5) aircraft and satellite remote sensing.

Autonomous Fixed Platforms

NOAA's moored buoys, deployed in U.S. estuarine and coastal waters and in the open Atlantic and Pacific Oceans (Figure 2) provide meteorological and oceanographic observations serving missions related to weather warnings and forecasts, climate monitoring and forecasting, safe and efficient marine transportation, and coastal resource management:

- The National Data Buoy Center (NDBC) has operated moored buoys in coastal and the deep oceans since the early 1970s. These 79 moored systems are fully automated and operate unattended from six months to four years. The observation suite was expanded in the early 1980s with 58 fully automated Coastal Marine Automated Stations (C-MAN) affixed to the land or sea floor. While the NDBC systems are designed primarily support weather forecasts and warnings, quality control efforts allow their use data for climate as well. These stations automatically report wind, barometric pressure, air temperature and relative humidity each hour. All buoys and some coastal stations also report sea temperature and state and some platforms also measure ocean currents and conductivity.
- The National Estuarine Research Reserve System-Wide Monitoring Program (SWMP), operated through coastal states, consists of moored platforms measuring pH, conductivity, water temperature, dissolved oxygen, turbidity, nutrients, chlorophyll, and water level at several sites within each of its 25 estuarine reserves, covering over one million acres. SWMP currently focuses on short-term variability and long-term changes in these key properties, and is expanding (albeit not with autonomous systems) to include changes in bio-diversity, land cover, and habitat in support of the Coastal Zone Management program.
- The National Current Observation Program (NCOP) measures currents in ports, harbors, and the Gulf Stream with current meters and moorings deployed at various locations for varying periods of time at critical locations identified by the user community. The data are used to develop and maintain tidal current predictions for approximately 2700 locations around the United States.
- Using the building blocks of NCOP and the National Water Level Observation Network (NWLON), described below, the Physical Oceanographic Real-Time System (PORTS®) provides real-time oceanographic and meteorological data, nowcasts, and forecasts in several

Figure 3. *Deploying an ATLAS buoy.*

major ports. While its primary mission has been to support coastal navigation, it is also being used to support chemical spill trajectory models and forecasts of harmful algal bloom landfall.
- The Tropical Atmosphere Ocean (TAO) moored buoy network in the tropical Pacific, begun in the mid 1980s by the Pacific Marine Environmental Laboratory (PMEL), is a key element of the El Niño/Southern Oscillation (ENSO) Observing System (McPhaden et al, 1998). The array was implemented through multi-national partnerships for improved detection, understanding, and prediction of El Niño and La Niña, and is presently operated jointly as the TAO/TRITON array with the Japan Marine Science and Technology Center. These moorings (Figure 3) routinely measure ocean temperature, surface air temperature, humidity, and wind and at many locations serve as platforms for salinity, currents, carbon dioxide, surface radiation, atmospheric pressure, and rainfall sensors. PMEL has provided TAO-like systems to French and Brazilian partners who, together with PMEL, maintain the Pilot Research Array in the Tropical Atlantic (PIRATA), and there is interest in expanding into the Indian Ocean, growing the tropical network from 77 to 119 stations over the next several years.
- NOAA and its national and international partners support several sites in the Global Eulerian Observatories (GEO) network, a coordinated effort to establish high-accuracy, long-term, and continuous reference time series in key climatic and biogeophysical regimes of the world ocean, including physical oceanographic and meteorological measurements; surface fluxes of heat, moisture, momentum, and carbon; biological productivity; changes in meridional overturning circulation; and biological and geophysical bottom processes. The plan calls for a permanent network of over 60 stations, with 29 designated as multi-disciplinary observatories as part of the National Science Foundation's pending Ocean Observatories Initiative (National Research Council, 2003).
- The Deep-ocean Assessment and Reporting of Tsunamis (DART) array includes six Pacific moored surface buoys, each with a surface communications relay and a bottom pressure recorder (BPR) that measures water pressure on the sea floor to calculate the height of the water column above it. The BPR is capable of detecting subtle water level fluctuations that might indicate passage of energy due to a tsunami and, through the acoustic link between the BPR and surface buoy, provide reports transmitted to land via the NOAA GOES communication system.

Tide Station Networks

NOAA supports two integrated systems for measuring changes in tides and water levels, one primarily supporting marine transportation and one supporting the climate change:
- The National Water Level Observation Network (NWLON) collects water level, meteorological, and oceanographic observations for 175 stations along the U.S. coast, including the Great Lakes and U.S. possessions and territories. It is the primary observing system for establishing tidal reference datums and its most well-known product, Tide Prediction Tables. While routine water level averages, collected every six minutes and reported hourly are the fundamental measurements, event-driven capabilities allow for reporting real-time observations of storm surge and tsunami events. Because several NWLON stations have continuous records for over 100 years, they also serve as a reference network for estimating relative sea level trends for the nation.
- NOAA contributes significantly to the international network of 199 stations that accurately measure sea level to calibrate and validate satellite altimeters and global climate models, and to document seasonal to centennial variability in ENSO, Indian Ocean and Asian-Australian monsoons, tropical Atlantic variability, North Atlantic Oscillation, North Pacific variability, western boundary currents, and circulation through straits and other ocean current choke points. NOAA and its international partners plan to upgrade 86 stations in the next few years with newer technology, including the global positioning systems (GPS).

Oceanographic Vessels and Ships of Opportunity

There is a wide range of sustained observations taken from aboard both large and small oceanographic vessels of the NOAA and non-NOAA fleet:
- NOAA Fisheries Ecological and Living Marine Resources observing system uses about 2000 days at sea (Figure 4) annually and additional time on charter vessels to collect standardized abundance, distribution, demographic, gut content, and condition data on living marine resources (e.g. more than a thousand species of fish and shellfish,

marine mammals, sea turtles) with representative sampling of over a million square miles of the U.S. EEZ and the Antarctic. Additional data are collected simultaneously on physical and chemical ocean properties, and on lower trophic levels (primary production and zooplankton abundance) of marine ecosystems. Depending on the region and taxonomic group, surveys are conducted from multiple times per year to every few years. For most regions time series are at least a decade long; some more than 50 years. Cooperation with Canadian and state programs that have adopted NOAA's protocols adds substantially to survey coverage in time and space.

- NOAA Fisheries also places Vessel Monitoring Systems (VMS) on commercial fishing vessels to transmit data via satellite on position and other information needed for research and management. In some cases, data on fisheries catch and discards is reported, and interfacing these systems with ship sensors for weather, sea temperature, and other observations would expand observations considerably. The trend worldwide is to increase use of VMS.
- Hydrographic surveys, from both NOAA and contract vessels, routinely determine water depths, submerged hazards, and the composition of the sea floor, such as sand, mud, or rock for high priority areas of the coastal U.S. While the primary end-products are nautical charts that enable safe navigation, efforts to expand the capabilities to include habitat characterization are underway. High-resolution mulitbeam data are proving to be useful to fisheries management by enabling benthic habitat mapping and characterization.
- The National Status and Trends Mussel Watch program monitors chemical contamination in sediments, mussels, and oysters in coastal U.S. waters. Samples collected at about 250 coastal and estuarine locations approximately every 2 years are analyzed for chemical contaminants, including DDT, chlordane, PCBs, and other indicators of human activity.
- The Ship of Opportunity Program (SOOP) provides upper ocean temperature, sea chemistry, and surface meteorology for determining long-term changes in marine climate and for supporting climate and weather forecasting. SOOP also provides platforms for routine deployment of drifting buoys and floats. NOAA is working to improve the accuracy of instruments on the global SOOP fleet, including a subset of high accuracy, high frequency, high resolution transect lines focused on upper ocean and atmospheric measurements. The number of SOOP lines is expected to increase from 23 to over 40 by 2007 in cooperation with international partners.

Figure 4. *Fisheries Vessel at work.*

- The Voluntary Observing Ship (VOS) program obtains weather observations from vessels traveling the world in the normal course of their business. The VOS program relies on voluntary ships' crew members to measure barometric pressure, air temperature, relative humidity, sky condition, precipitation, obstructions to vision, and sea state, every 3 or 6 hours. The observations are logged and transmitted either via voice radio or by PC connected to communications modem.
- Fisheries Observer Programs place trained observers on commercial fishing vessels to collect data on fishing operations, catch, discards, and physical ocean properties. Thousands of days of fishing are observed annually throughout U.S. coastal waters, and on the high seas.
- Continuous plankton recorders (CPRs) have been deployed from ships of opportunity for more than 60 years beginning with European efforts for the North Sea and North Atlantic. CPRs are deployed from ship of opportunity for transects across the Gulf of Maine and from New York to Bermuda for nearly 50 years.

Drifting Surface Buoys and Profiling Systems

Expendable drifting buoys and sub-surface profiling floats provide broad spatial coverage of key ocean and surface meteorological properties via satellite relay:

- NOAA supports 600 of the currently deployed international global network of 800 surface drifters. Plans exist to expand this array to 1250 by 2005. The unit cost and number of observations from these modern surface drifting buoys make them an economical alternative for obtaining sea surface temperature and surface currents, and in some cases air pressure measurements.
- Profiling floats that remain submerged for extended periods at a specified "parking depth" (typically 2000 m), then surface on a regular schedule to transmit data to shore via satellite. The floats provide profiles on a globally distributed basis of temperature and salinity, two fundamental state variables of the climate system. The floats also provide information on the velocity field at

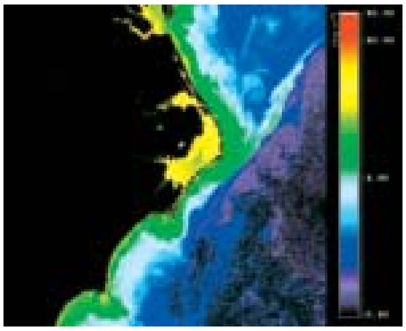

Figure 5. *Increased coastal ocean chlorophyll levels (shown here in yellow-to-orange) are evident in this post Hurricane Floyd satellite imagery over eastern North Carolina on September 26, 1999. Image Credit: NOAA analysis. Imagery is from the SeaWiFS multispectral imaging satellite, provided through contract with Orbimage, Inc.*

their parking depths from differences in satellite position fixes between sequential ascents. As of June 2003, 825 of these floats are in operation as part of the Argo Program (Argo Science Team, 2001); plans call for 3000 to be deployed globally by 2005, half of them provided by the U.S.

Remote Sensing

Remote sensing from aircraft and satellites is a key component of NOAA's ocean observing programs and it is anticipated the dependence on these assets will grow as new platforms and sensors become available. Current efforts include:

- NOAA's environmental satellite program provides global ocean data sets of temperature, winds, chlorophyll, sea elevation, and other parameters from both operational NOAA and international partner, NASA research, and (through contract arrangements) commercial satellites. High resolution imagery, such as that shown here for post hurricane Floyd chlorophyll plumes in Figure 5, are now becoming increasingly available. This next generation of highly-resolving observational capabilities is embodied in the new federal inter-agency National Polar-orbiting Operational Environmental Satellite System (NPOESS), and opens new doors on coastal and ocean observations from space.
- NOAA's Coastal Change Analysis Program (C-CAP) uses satellite imagery to classify and map land cover in coastal upland and wetland habitats. Done routinely over time, the program reports changes in land and wetland cover.
- The National Geodetic Survey uses aerial photography and LIDAR to survey and delineate the approximately 95,000 miles of U.S. coastline, providing an accurate, consistent, and up-to-date national shoreline.
- NOAA conducts surveys of the abundance of marine mammals and sea turtles from NOAA aircraft. These data are critically important for tracking the status of these NOAA trust resources, and for operational aspects of conservation programs, such as alerting the ships about the location of endangered right whales so as to minimize ship strikes.

NOAA and the Emerging Integrated Ocean Observing System

GOOS planning over the past decade evolved from an architecture of five modules (climate, marine services, health of the ocean, living marine resources, coastal ocean) to two: Global and Coastal. In practice, the former Climate module has become the Global module and the remaining four have been integrated into the Coastal module. There are important similarities in many of the challenges of developing both modules: system design is hampered by poorly defined and understood target phenomena, inadequate knowledge of time and space scales that need to be resolved, technological gaps between what needs to be measured and what can be measured cost-effectively, and the need for multi-disciplinary measurements to characterize existing conditions and forecast their evolution. There are additional challenges in integrating research and modeling with sustained measurement programs, in developing mechanisms to transition research systems to operational status, and in developing international partnerships needed to sustain long term observational efforts. Finally, there are major jurisdictional challenges in ensuring access to and coordinating observational efforts within the Exclusive Economic Zones of nations bordering the oceans.

Even with these challenges, NOAA's contribution to an integrated ocean observing system is clear and strong. NOAA's buoys, tide stations, and satellites are already key components of the existing global network and through planned enhancements they will continue to flesh out the backbone of the next generation integrated climate observing system. In Coastal waters, NOAA's decades of experience surveying living marine resources and their biotic and abiotic environment are widely recognized and emulated.

NOAA also recognizes that global cooperation is essential to implement and realize the benefits from both the Global and Coastal observing system modules of an integrated system. The recent Earth Observation Summit initiated by the United States was a bold initiative to elevate commitment to international cooperation for earth observations. We look forward to the new opportunities that will result.

While there are similar challenges for the design of both the Coastal and Global modules, there are also important differences. For example, technological advances have made measurement of many physical and chemical variables feasible in real (or near real) time, with both resolution and coverage that could only be imagined a decade or so ago. Yet, technology for making biological measurements, particularly for higher trophic levels, has proven to be much more problematic, and these biological measurements are far more important for the Coastal Module. Fortunately, real time information is not needed for many important coastal applications. There are also major jurisdictional complications even within the U.S. coastal zone.

One challenge NOAA faces in contributing to the Coastal module is that there is less clarity on what will constitute it. The current list of variables identified by the Intergovernmental Oceanographic Commissions plan for the Coastal module is a short list of variables that are purported to be important everywhere, but we believe that by themselves they would be inadequate to meet the needs of many of the coastal users the system is intended to serve. Former Speaker of the House Tip O'Neal pointed out that "… in politics, everything is local," and this is also true for coastal observations. That perspective dominated development of many existing coastal observing programs, including NOAA's, and it will likely determine the success of the integrated Coastal module. While the IOOS goal is to put in place an integrated, scientifically-based coastal ocean observing system for the U.S. (and ultimately globally), its success will depend on the value realized, and utility perceived, by its diverse local users from government and non-governmental organizations, commercial interests, and the general public.

While many coastal phenomena are globally ubiquitous (e.g., overfishing, nutrient enrichment, storm surges), few can be monitored or modeled at that scale because most are forced locally. Giving priority in the Coastal module to variables that are important everywhere produces an inherently small set of variables (consider that there are virtually no marine animals with a global distribution, and very few that are national for the U.S.) that may be relevant nationally, but are less relevant to fulfilling many local and regional goals. While certain general physical properties are important to coastal communities (e.g. water levels, currents, temperatures) these are but a small subset of the properties that matter to them (Heinz Center, 2002). Instead, coastal issues are dominated by biological phenomena and many more biological variables that are difficult to measure (e.g., abundance and species of plants and animals, demographic information about individual animals such as age and size) where real time information is neither feasible nor often necessary.

Finally, and probably most important, many potential elements of the Coastal module have existed for decades, or longer. For example, Continuous Plankton Recorder surveys of the North Atlantic have been conducted for more than sixty years. CalCOFI surveys of plankton of the California Current are about fifty years old. Fishery resource surveys off the Northeastern U.S. began forty years ago, and physical, chemical and plankton observations have been collected simultaneously for most of the time. Worldwide, there are many valuable time series of coastal data that were initiated (often decades ago) to help fulfill what has become the goals of the Coastal Module. Thus, significant portions of a coastal ocean observing system already exist, particularly for the United States. An important challenge is to take advantage of them, as opposed to focusing primarily on adding new efforts focused on the small set of common variables. There are many threats to these existing programs (e.g., reduction in funding from the state of California threatens CalCOFI), their quality assurance is variable (almost certainly inadequate in some cases), and documentation may be insufficient. There are needs to modernize observing technologies and fill gaps as important data are not collected in some areas, or the data density is insufficient (either spatially or temporally). Databases need to be integrated and access needs to be improved. As such, the Coastal module, particularly those elements focused on high priority biological and chemical properties and phenomena, should emphasize value-added protocols (e.g., quality assurance, statistical design, observing and information technology advances) to be used by regional or local observing systems, rather than top down focus on variables to be measured everywhere. In reality, local and regional observing systems that serve user needs will ultimately be the backbone of the Coastal module.

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